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14. ABSTRACT
Transient plasma discharges utilizing short (30 to 100 nsec), spatially distributed streamers energized by pulsed power were investigated as a potential new method for flame ignition. Experimental results showed shorter ignition delay and pressure rise time (typically by a factor of 3 for methane-air mixtures), as well as higher maximum pressure compared to conventional spark ignition. In all cases significant modification of initial combustion chemistry appeared to be occurring, leading to more effective combustion over a wider range of pressures and fuel composition rates.

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"Energy-Efficient Transient Plasma Ignition & Combustion"

AFOSR Grant No. F49620-01-1-0322,

M. Gundersen, P.I. mag@usc.edu

June 1, 2001 – November 30, 2003

STATUS OF EFFORT, ACCOMPLISHMENTS and NEW FINDINGS

Transient plasma discharges utilizing short (30 to 100 nsec), spatially distributed streamers energized by pulsed power have been investigated as a potential new method for flame ignition. Experimental results show shorter ignition delay and pressure rise time (typically by a factor of 3 for CH_4/Air), as well as higher maximum pressure compared to conventional spark ignition. These benefits might be of interest for many combustion applications.

In all cases significant modification of initial combustion chemistry appears to be occurring, leading to more effective combustion over a wider range of parameters, such as pressure and fuel composition. Such effects can have significant impact on operation of a rocket, gas turbine, or combined cycle engines, by extending capability and by stabilizing transitions between phases.

Based on studies of quiescent fuel mixtures at the University of Southern California (USC), off-campus studies of pulse detonation engine (PDE) ignition at the Naval Postgraduate School (NPS), and initial studies of transient plasma enhanced radical production, we conclude that transient plasmas have strong potential for improved ignition, flameholding, and other combustion enhancement. Future work is planned specifically to delineate the production and effect of key species. Collaborations are planned to address diagnosis, fuel mixing strategies, and theoretical support necessary to develop fundamental understanding and provide a pathway to implementation.

Publications and Presentations of Research Findings

Publications

"Premixed Flame Ignition By Pulsed Corona Discharges," J. Liu, P.D. Ronney, and M. Gundersen, Western States Section, The Combustion Institute, 2002 Spring Meeting, March 25-26, 2002.

"Compact Nanosecond Pulse Generator for Pseudospark Based Pulse Generator for Corona Assisted Combustion Experiments," A. Kuthi, J. Liu, C. Young, and M. Gundersen, Proceedings of the 2002 International Power Modulator Conference and High Voltage Workshop, June 30-July 3, 2002, Hollywood, CA, pp. 667-670.

"Transient Plasma Ignition For Lean Burn Applications," J.B. Liu, P.D. Ronney, F. Wang, L.C. Lee, and M.A. Gundersen, Proceedings of 2003 American Institute of Aeronautics and Astronautics, 41st Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 2003, No. 2003-6208.

"Premixed Flame Ignition by Transient Plasma Discharges," J.B. Liu, P.D. Ronney, and M. Gundersen, Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, Illinois, March 16-19, 2003. Paper B-25.

"Pseudospark Based Pulse Forming Circuit For Transient Plasma Ignition And Combustion Control Systems", F. Wang, A. Kuthi, C. Jiang, and M. Gundersen, Proc. 14th IEEE International Pulsed Power Conference, Dallas, TX, June 15-18, 2003, pp. 339-342.

"Rapid Charger For High Repetition Rate Pulse Generator", A. Kuthi, C. Young, F. Wang, P. Wijetunga and M. Gundersen, Proc. 14th IEEE International Pulsed Power Conference, Dallas, TX, June 15-18, 2003, pp. 950-952.

"Minimum ignition energies and burning rates of flames ignited by transient plasma discharges," J. B. Liu, N. Theiss, P. D. Ronney, and M. A. Gundersen, 2003 meeting of Western States Section/Combustion Institute, UCLA, Oct 10-11, 2003, Paper 03F-88.

"Transient Plasma Ignition of Ethylene-Air and Propane-Air Mixtures in Pulse Detonation Engines," F. Wang, C. Jiang, A. Kuthi, M. Gundersen, C. M. Brophy, J. O. Sinibaldi, and L. C. Lee, Proceedings of the 16th ONR Propulsion Meeting, Los Angeles, CA, June 9-11, 2003, pp. 143-148.

"Combustion Characteristics of a Multiple Swirl Spray Combustor," E. J. Gutmark, G. Li, X. Zhou, M. Lin, J. B. Jeffries, R. K. Hanson, F. Wang, and M.Gundersen, Proceedings of the 16th ONR Propulsion Meeting, Los Angeles, CA, June 9-11, 2003, pp. 73-81.

"Effect of discharge energy and cavity geometry on flame ignition by transient plasma", J.B. Liu, F. Wang, L.C. Lee, N. Theiss, P.D. Ronney, and M.A. Gundersen, to appear in Proceedings 2004 American Institute of Aeronautics and Astronautics.

"Effect of fuel type on flame ignition by transient plasma discharges", J.B. Liu, F. Wang, L.C. Lee, P.D. Ronney, and M.A. Gundersen, to appear in Proceedings 2004 American Institute of Aeronautics and Astronautics.

"Transient Plasma Ignition of Hydrocarbon-Air Mixtures in Pulse Detonation Engines", F. Wang, C. Jiang, A. Kuthi, M.A. Gundersen, C. Brophy, J. Sinibaldi, and L.C. Lee, to appear, Proc. 2004 American Institute of Aeronautics and Astronautics.

Presentations

Invited

Presentation to the Plasma Sciences Committee of the National Academies of Science and Engineering, "Physics and Applications of Partially Ionized Plasmas: Research Needs", M. Gundersen, Beckman Center, National Academies of Science and Engineering, Irvine CA, September 30, 2001.

"Ultrashort Electric Perturbations Trigger Membrane Phospholipid Translocation and Apoptosis," P. T. Vernier and M. A. Gundersen, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH, 2002.

"Transient, or True Non-Thermal, Plasma-Enhanced Ignition of Fuel Mixtures, and Emission Reduction," presented by M. Gundersen at Gordon Conference on Plasma Processing Science, Tilton, New Hampshire, July 21-25, 2002.

"Compact, Portable Pulsed Power: Physics and Applications", M. Gundersen, J. Dickens, and W. Nunnally, Plenary presentation for the 2003 IEEE Pulsed Power Conference, June 16, 2003.

"Transient Plasma Ignition," M. Gundersen, presented to Boeing – Rocketdyne Propulsion & Power, July 15, 2003.

"Physics and Applications of Pulsed Power", M. Gundersen, presented to the Physics Department of the Naval Postgraduate School, August 2003.

"Challenges and Overview", M. Gundersen, Workshop on Understanding Plasma Ignition, Stanford University, Jan. 9, 2004.

"Pulsed Power: Physics, and Two Diverse Applications", M. Gundersen, Lawrence Berkeley Laboratory, February 17, 2004.

Contributed Presentations

"Transient, or True Non-Thermal, Plasma-Enhanced Ignition of Fuel Mixtures," presented by M. Gundersen at ONR Review, Washington, D.C., August 5-7, 2002.

"Pseudospark-Based Pulse Generation for Ignition," F. Wang, A. Kuthi, and M. Gundersen, IEEE Intl. Power Modulator Conference, Hollywood, CA, July 2, 2002.

"Transient Plasma Ignition for Lean Burn Applications," J. B. Liu, P. D. Ronney, A. Kuthi, F. Wang, L. C. Lee, and Martin Gundersen, presented at the 41st AIAA Meeting, Jan. 6-9, 2003, Reno, Nevada.

"Transient Plasma Ignition for Pulsed Detonation Engines," J. B. Liu, P. D. Ronney, A. Kuthi, F. Wang, L. C. Lee, and Martin Gundersen, presented by A. Kuthi at ONR Review Meeting, Jan. 11, 2003, Monterey, California.

"Premixed Flame Ignition by Transient Plasma Discharges," J.B. Liu, P.D. Ronney, and M. Gundersen, Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, Illinois, March 16-19, 2003.

"Transient Plasma Ignition for Pulse Detonation Engines," presented by M. Gundersen at 16th ONR Propulsion Meeting, University of Southern California, June 9-11, 2003.

"Pseudospark Based Pulse Forming Circuit For Transient Plasma Ignition And Combustion Control Systems", F. Wang, A. Kuthi, C. Jiang, and M. Gundersen, Proc. 14th IEEE International Pulsed Power Conference, Dallas, TX, June 15-18, 2003, pp. 339-342.

"Rapid Charger For High Repetition Rate Pulse Generator", A. Kuthi, C. Young, F. Wang, P. Wijetunga and M. Gundersen, Proc. 14th IEEE International Pulsed Power Conference, Dallas, TX, June 15-18, 2003, pp. 950-952.

"Minimum Ignition Energies and Burning Rates of Flames Ignited by Transient Plasma Discharges," J. B. Liu, N. Theiss, P. D. Ronney, and M. A. Gundersen, 2003 meeting of Western States Section/Combustion Institute, UCLA, Oct 10-11, 2003.

"Effect of Fuel Type on Flame Ignition by Transient Plasma Discharges", Jianbang Liu, Fei Wang, Long C. Lee, Paul D. Ronney, and Martin A. Gundersen, 42nd Aerospace Sciences Meeting, 6th Weakly Ionized Gases Workshop, Reno, Nevada 5 - 8 Jan 2004.

"Effect of Discharge Energy and Cavity Geometry on Flame Ignition by Transient Plasma", Jianbang Liu, Fei Wang, Long C. Lee, N. Theiss, Paul D. Ronney, and Martin A. Gundersen, 42nd Aerospace Sciences Meeting, 6th Weakly Ionized Gases Workshop, Reno, Nevada 5 - 8 Jan 2004.

"Transient Plasma Ignition of Hydrocarbon-Air Mixtures in Pulse Detonation Engines", F. Wang, C. Jiang, A. Kuthi and M. A. Gundersen C. Brophy and J. O. Sinibaldi, L. C. Lee, 42nd Aerospace Sciences Meeting, 6th Weakly Ionized Gases Workshop, Reno, Nevada 5 - 8 Jan 2004.

These publications and presentations were either fully or partially supported by the AFOSR. Support also was provided by the Army Research Office (Dr. David Skatrud) and the Office of Naval Research (Dr. Gabriel D. Roy).

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

U.S. Patent Application Serial No. 60/336,799 "Flame Igniter by Transient Plasma", USC File #3232.

HONORS/AWARDS

Behrend, Matthew: Achievement Rewards for College Scientists 2002, Outstanding Undergraduate Research Achievement Award of the 2002 IEEE Power Modulator Conference.

Behrend, Matthew and Thu, Mya Mya Sein, 1st Place, 2002 USC Undergraduate Research Program.

B. CONSULTATIVE AND ADVISORY FUNCTIONS TO OTHER LABORATORIES AND AGENCIES

Visiting Professor, Physics Department, The Naval Postgraduate School, 2003-04.

C. TRANSITIONS. DESCRIBE CASES WHERE KNOWLEDGE RESULTING FROM YOUR EFFORT IS USED, IN A TECHNOLOGY APPLICATION.

Collaborations have been initiated with the Air Force Research Laboratory Propulsion Directorate at Wright- Patterson Air Force Base (AFRL/PR), including work with Drs. Ganguly, Carter, and discussions with Drs. Jackson, Rivir, and others at that location. The collaborations included participation in research at that location by Prof. Long Lee during summer of 2002. Interactions with other DoD laboratories include the Naval Postgraduate School (D. Netzer, C. Brophy, J. Sinibaldi), and universities including the University of Cincinnati (E. Gutmark) and Stanford University (R. Hanson).

Dr. Ganguly is studying the dissociative excitation processes of CH_4 by energetic electrons in high-voltage-pulsed-discharged plasma. Electrons with energy up to 50 eV are inferred in his experiments. His observations correlate well with our experiments – he has reported that active chemical species are produced through dissociative excitation of fuels (hydrocarbons) and oxygen (in air) by higher-energy electrons existing in non-thermal plasmas. We also have also provided recently a pseudospark-based pulse generator to Dr. Ganguly for some of these studies. Dr. Carter is interested in testing our high-voltage-transient-discharge system in the supersonic combustion facility at AFRL/PR.

PERSONNEL SUPPORTED

Professor Martin Gundersen	Professor/Department Chair
Professor Paul Ronney	Professor, Aerospace & Mechanical Engineering
Prof. Long Chi Lee	Professor, EE, San Diego State University
Dr. Andras Kuthi	Senior Research Associate
Dr. Jianbang Liu	Research Associate Professor
Mr. Matthew Behrend	Undergraduate Research Assistant
Mr. Fei Wang	Graduate Research Assistant
Dr. Chunqi Jiang	Postdoctoral Research Associate

SUMMARY OF THE RESEARCH

Transient plasma discharges were studied for application to the ignition and combustion of fuels. The phrase "transient plasma" refers to a transitional phase of plasma, occurring during the formative phase of an electrical discharge and typically lasting 10's of nanoseconds. For these studies, during the transient phase, an array of streamers was produced. Streamer-initiated combustion was studied for a variety of fuels, under varied operating conditions, described in more detail below.

It was found that improved ignition over a broad range of conditions occurs employing this transient phase of plasma for ignition. Substantially reduced ignition delay times (factors of 3X were typical [1-3], and under some flowing conditions, even more reduction [4]) and other useful results were achieved, partially by employing advanced power conditioning technology [5-7]. The method did not require excessive energy for implementation.

As an example, experimental results showed that transient plasma discharge resulted in shorter ignition delay and pressure rise time (typically by a factor of 3 for CH_4/Air quiescent mixture [2, 3, 8] and even more for flowing pulse detonation engine ethane-air mixtures [4, 8, 9]). We conducted experiments in quiescent fuel air mixtures including methane, ethane, propane, butane and octane for various equivalence ratios. Further benefits included higher maximum pressure, indicative of improved efficiency. Pulse energies were typically 50 mJ to 1 J, demonstrating that energy requirements were comparable to traditional spark ignition.

The rise and delay times of mixtures of methane, propane, n-butane, iso-butane and iso-octane mixed with air ignited by transient plasma discharges were investigated and compared with spark discharge ignition. The *transient plasma* discharges cannot be produced by conventional ignition systems [10, 11]. Moreover, the ignition method examined here is entirely different from "plasma jets [12]," whereby sparks are discharged in a prechamber (sometimes containing different reactants) and radials/ions thereby generated expand via gasdynamics into the main combustion chamber. The system for quiescent studies has no prechamber or auxiliary reactants.

A major difference between pulsed transient plasma discharges and spark discharges that is visually apparent is the production of multiple simultaneous discharge channels. This volume distribution causes the initial phase of ignition to occur over a large (compared to spark discharge) spatial volume, thus making spatially extensive ignition possible. The number of streamer discharge channels can be higher than 100.

A further major difference is that a significant fraction of electrons in the head of a streamer have higher electron energy than a spark discharge [13, 14]. The electron energy distribution of a streamer occurring during the transient phase is very inhomogeneous in space and time. However, the streamer head will have a high electric field, which is responsible for ionization and the formation of a plasma. The electron energies are sufficient for not only ionization, but also dissociation of hydrocarbons, as well as radical production. Therefore, it is reasonable to consider transient plasma for the production of spatially extended ignition and higher burning rates.

Experimental Setup and Results

A typical experimental setup used for transient plasma discharge studies in quiescent mixtures is shown in Figure 1. A pulsed corona discharge was created by a high voltage pulse generator, which provides typically of 60 KV peak voltage, 100 ns pulse width (using a thyratron switch) or 50 ns (using a pseudospark switch). A commercially available ignition circuit was also used for comparisons. These experiments are described in more detail in references 1-4. The pressure history was measured with a pressure transducer (ASCX) with response time of 0.1ms (for the cylindrical combustion chamber) or with a Kistler pressure transducer (for a pancake combustion chamber) with 100 KHz response frequency. Voltage and current were measured with a voltage divider (1000:1) and a current transformer (0.1V/A). Pressure, voltage and current signals were recorded with a digital oscilloscope (Tektronix 640C). The electric pulse energy was calculated from product of voltage and current integrated with respect to time.

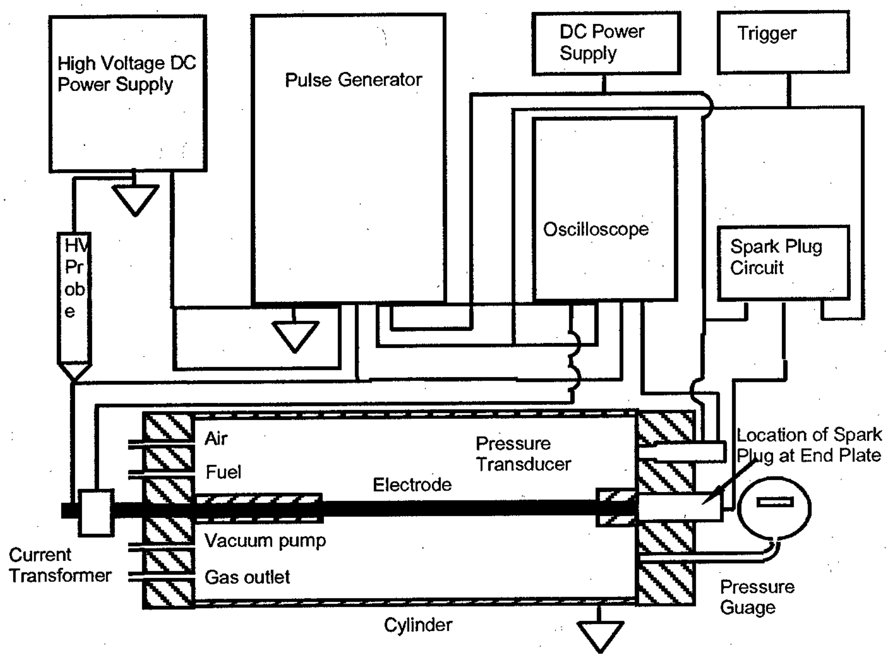

Fig.1. Experiment setup and cylindrical combustion chamber.

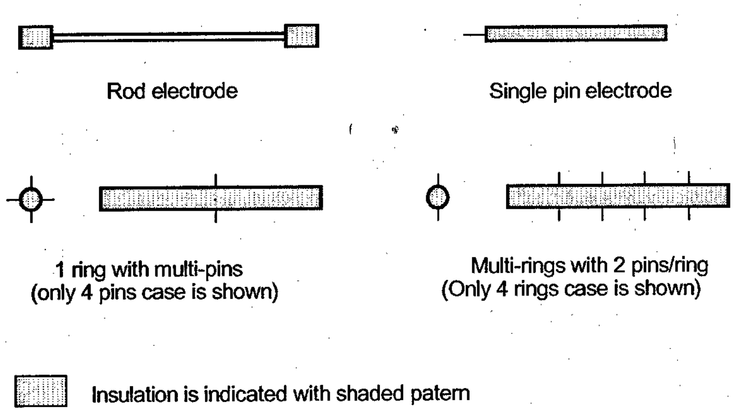

Fig. 2. Various inner electrode configurations for the cylindrical combustion chamber

In the cylindrical combustion chamber, experiments were conducted for four kinds of electrodes (Fig.2): single pin, 1 ring with multi pin, multi ring with 2 pins each ring, and rods. Different electrode structures were intended to produce different numbers of ignition sites. In the single pin electrode case, the corona discharge concentrates in a narrow space volume, even though the corona discharge is still multi-channeled. Therefore, the single pin electrode experiments show single ignition site effects. 1 ring with multi-pin electrode and multi-ring with 2 pins per ring electrodes were intended to show multi-ignition site effects. The rod electrode results in many (10s to 100s) discharge channels simultaneously. For comparison, a spark discharge gap was used that has a 1mm gap and was located either at the center or on the end plate of the combustion chamber.

A pressure transducer (Omega PX4201) with 0.2ms response time was adopted, along with a digital oscilloscope (Tektronix TDS 420A) to measure the pressure waveform. The delay time (defined as the time lapse between the trigger and the pressure rise to 10% of its total pressure rise), rise time (defined as the time lapse between the pressure rise to 10% and 90% of its total pressure rise), and peak pressure were measured from pressure waveforms.

Typical delay and rise times versus energy for discharges in stoichiometric CH_4/air and other fuels are shown in the data included as an Appendix. As the energy increased, the delay time decreased slightly, and the rise time was observed to become significantly faster with increasing energy. There is an energy value (e.g. typically 350 mJ) above which the rise time has its smallest value and remains almost constant. Below this value, rise times are relatively long and scatter. This energy level is the "optimum energy" because it produces the shortest stable rise time with the lowest energy. The optimum energy is higher for leaner mixtures.

Iso-octane-air mixtures showed behavior similar to the other fuels. As shown in the appendix, over a wide range of equivalence ratios (0.8-1.4) and initial pressures (0.2-1.0 atm), the delay time and the rise time of pulsed corona-ignited flames are shorter than those of spark ignited flames.

To compare ignition behavior between pulsed corona and spark discharges more explicitly, an improvement factor of delay time (rise time) was defined as the ratio of delay times (rise times) of flames ignited by spark discharges and pulsed corona discharges. For methane-air mixtures, the average values of improvement factors of delay times and rise times over an equivalence ratio range of 0.7-1.2 are 3.0 and 3.8, respectively. For iso-octane-air mixtures, the improvements are 2.5 and 2.4, respectively, over an equivalence ratio range of 0.9 to 1.4.

The low pressure ignition limit, defined as the lowest pressure under which the flame is ignitable in our pulsed corona discharge ignition device, for both methane-air and iso-octane-air, is 0.1 atm in the stoichiometric case and varies from 0.1atm. to 0.4 atm. for an equivalence ratio range from 0.7 to 1.4 for methane-air mixtures or from 0.1 atm. to 0.2 atm. for an equivalence ratio range from 0.8 to 1.4 for iso-octane-air mixtures. We believe that this may be of interest for high altitude relight applications

DISCUSSION

Experiments show that corona discharge ignition provides shorter (by typically 3x) delay and rise times than flames ignited by spark discharge, even at the most favorable spark location.

Geometrical advantages of pulsed corona ignition probably exist because pulsed corona discharge creates several hundred discharge channels, filling the chamber volume compared to one unnecessarily intense channel for spark discharges. If a significant fraction of these channels produce successful ignition kernels, the distance and time each kernel must travel to consume its share of combustible mixture is greatly reduced compared to a single spark, and thus delay and rise times are decreased.

The significantly shorter delay times suggest the possibility of creating initial conditions for ignition that are different from traditional ignition and enhancing the creation of excited species, such as radicals [15]. The presence of electrons with greater energy during the transient phase qualitatively suggests the possibility of dissociation of fuels into fragments, such as hydrogen. The microscopic processes involved are very complex, and it was not possible to discover the amount of fragments produced. Thus, it is of interest to not only exploit this methodology for possible applications, but to also endeavor to better understand the physics, through experimental and theoretical studies. The level of effort required for a thorough understanding of the microscopic processes is beyond the scope of the current effort, but can be addressed through future collaborative experimental and theoretical work.

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[1] "Transient Plasma Ignition For Lean Burn Applications," J.B. Liu, P.D. Ronney, F. Wang, L.C. Lee, and M.A. Gundersen, Proceedings of 2003 American Institute of Aeronautics and Astronautics, 41st Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 2003, No. 2003-6208.

[2] "Effect of Discharge Energy and Cavity Geometry on Flame Ignition by Transient Plasma", J.B. Liu, F. Wang, L.C. Lee, N. Theiss, P.D. Ronney, and M.A. Gundersen, to appear in Proceedings 2004 American Institute of Aeronautics and Astronautics.

[3] "Effect of Fuel Type on Flame Ignition by Transient Plasma Discharges", J.B. Liu, F. Wang, L.C. Lee, P.D. Ronney, and M.A. Gundersen, to appear in Proceedings 2004 American Institute of Aeronautics and Astronautics.

[4] "Transient Plasma Ignition of Hydrocarbon-Air Mixtures in Pulse Detonation Engines", F. Wang, C. Jiang, A. Kuthi, M.A. Gundersen, C. Brophy, J. Sinibaldi, and L.C. Lee, to appear, Proc. 2004 American Institute of Aeronautics and Astronautics.

[5] "Compact Nanosecond Pulse Generator for Pseudospark Based Pulse Generator for Corona Assisted Combustion Experiments," A. Kuthi, J. Liu, C. Young, and M. Gundersen, Proceedings of the 2002 International Power Modulator Conference and High Voltage Workshop, June 30-July 3, 2002, Hollywood, CA, pp. 667-670.

[6] "Pseudospark Based Pulse Forming Circuit For Transient Plasma Ignition And Combustion Control Systems", F. Wang, A. Kuthi, C. Jiang, and M. Gundersen, Proc. 14th IEEE International Pulsed Power Conference, Dallas, TX, June 15-18, 2003, pp. 339-342.

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[9] "Transient Plasma Ignition of Ethylene-Air and Propane-Air Mixtures in Pulse Detonation Engines," F. Wang, C. Jiang, A. Kuthi, M. Gundersen, C. M. Brophy, J. O. Sinibaldi, and L. C. Lee, Proceedings of the 16th ONR Propulsion Meeting, Los Angeles, CA, June 9-11, 2003, pp. 143-148.

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[13] A useful phenomenological description and insight into the physics of streamers may be found in "Yu Raizer", "Gas Discharge Physics", Springer-Verlag (2nd Ed. 1997).

[14] Related research on combustion initiated by a pulsed ionization wave, which is a different and more energy intensive approach but investigates the creation of excited and dissociated species, and similar physical processes during a short pulse, is being reported by the Russian group at the Moscow Institute of Physical Technology. See for example "Discharge Dynamics and the Production of Active Species in a Cathode-Directed Streamer", S.V. Panceshnyi, S. V. Sobakin, S. M. Starikovskaya, and A. Yu. Starikovskii, Plasma Physics Reports, Vol. 26, No. 12, 2000, pp. 1054–1065. Translated from Fizika Plazmy, Vol. 26, No. 12, 2000, pp. 1126–1138. See also "Nanosecond Gas Discharge Ignition of H_2 and CH_4 Containing Mixtures", S.A. Bozhenkov, S.M. Starikovskaia, and A.Yu. Starikovskii, Combustion and Flame 133 (2003) 133–146.

[15] "Combustion Characteristics of a Multiple Swirl Spray Combustor," E. J. Gutmark, G. Li, X. Zhou, M. Lin, J. B. Jeffries, R. K. Hanson, F. Wang, and M. Gundersen, Proceedings of the 16th ONR Propulsion Meeting, Los Angeles, CA, June 9-11, 2003, pp. 73-81.

APPENDIX: TABULATION OF COLLECTED DATA FOR TRANSIENT PLASMA IGNITION

"Energy-Efficient Transient Plasma Ignition & Combustion"
AFOSR Grant No. F49620-01-1-0322,
M. Gundersen, P.1. mag@usc.edu
June 1, 2001 — November 30, 2003

The appendix collects figures showing data for ignition of a variety of fuels and fuel conditions with transient plasma ignition, and provides comparisons with traditional spark ignition.

Figures 1-3 show the electrical characteristics of a pulsed, transient plasma (sometimes termed "corona") discharge in the apparatus for quiescent studies. In the data shown, the pulse generator provided a 50KV voltage pulse with 100 ns pulse width and 1 Joule energy. The apparatus is shown in the report. The figures also contrast performance with arc discharges.

Figure 4 shows the relation between energy and peak voltage of a transient plasma discharge for various electrode structures. Pulsed positive voltage produces much higher energy than negative at the same peak voltage. Thinner electrodes have lower intercept voltage than thicker electrodes, and brush like electrodes provide the highest energy compared to all the other tested electrode structures.

Figures 5-15 show combustion performance (ignition delay time, pressure rise time and peak pressure) for various fuel/air mixtures including methane, propane, iso-butane, n-butane and iso-octane, and comparisons with spark ignition. All tested fuel/air mixtures have shorter ignition delay (3x for CH_4/air) and pressure rise times (3x for CH_4/air) and higher peak pressure with pulsed corona ignition compared to spark ignition in a wide equivalence region (0.7-1.4 for CH_4/air) and initial pressure regions (0.2-1.0 atm. for CH_4/air).

Figure 16 presents data showing that an iso-octane/air mixture can be ignited with transient plasma at an initial pressure as low as 0.1 atm. over a very wide equivalence ratio region (0.9-1.4). This broadening might be of interest for high altitude relight of gas turbine engines.

Figures 17 and 18 show the minimum energy for transient plasma ignition variation with equivalence ratio, and initial pressure, for CH_4/air and C_3H_8/air. Note that CH_4/air can be ignited at initial pressures as high as 8 atm. (a pressure close to the pressure in automobile spark ignition engines before ignition) with moderate minimum ignition energy.

Figure 19 shows a comparison between transient plasma ignition with spark ignition in a combustion chamber geometrically similar to an automobile engine cylinder. The pulsed corona ignition has a shorter (2x) pressure rise time and higher peak pressure than that of spark ignition.

Figure 20 shows the discharge efficiency (the ratio between energy absorbed by a gas to the total discharge energy) over a wide energy range for various transient plasma and spark

discharges. The transient plasma has significantly (approximately an order of magnitude) higher discharge efficiency than that of a spark discharge.

Figure 21 shows pressure waveforms for a transient plasma discharge in turbulent flow conditions. Even in a turbulent flow, the transient plasma can ignite a CH_4/air mixture under a very lean condition (equivalence ratio: 0.65).

Figure 22 shows a comparison of pressure waveforms between transient plasma and spark ignitions in turbulent flow conditions. Pulsed transient plasma ignition has a shorter ignition delay time and a higher peak pressure than that of spark ignition.

I. Pulsed corona discharge performance

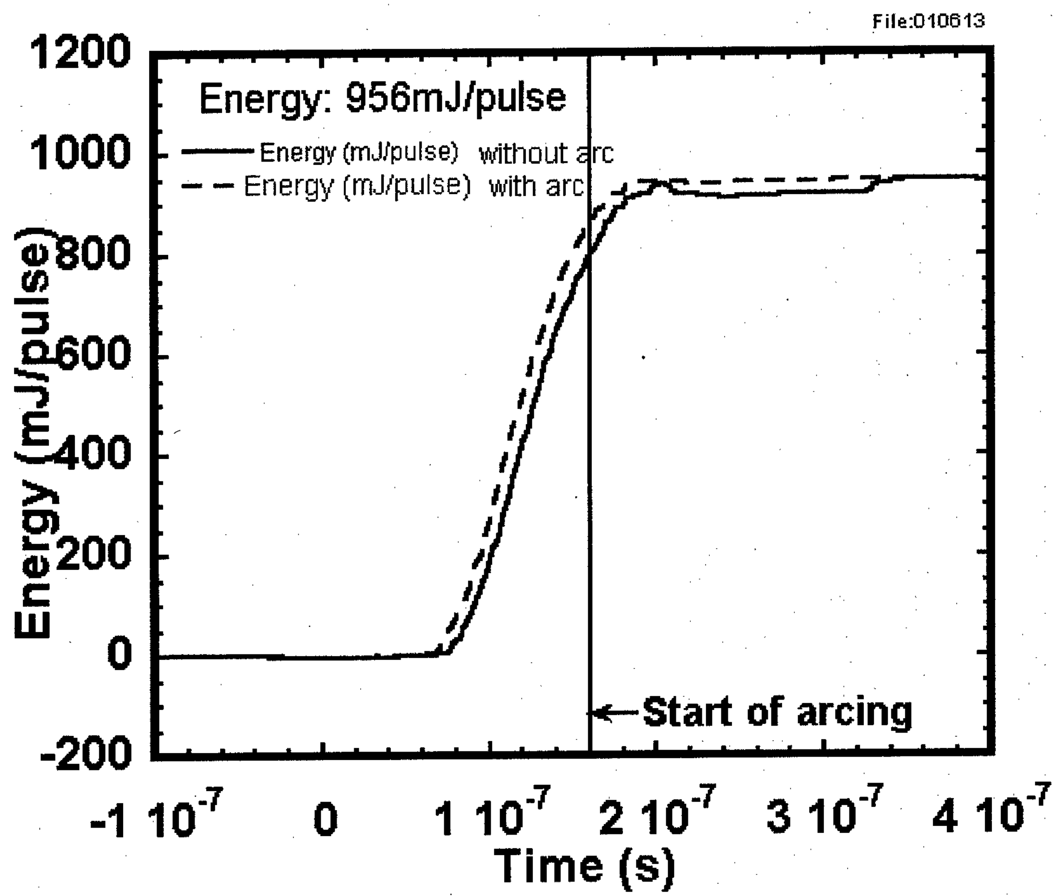

Figure 1: Transient plasma discharge waveforms: (a) energy vs. time.

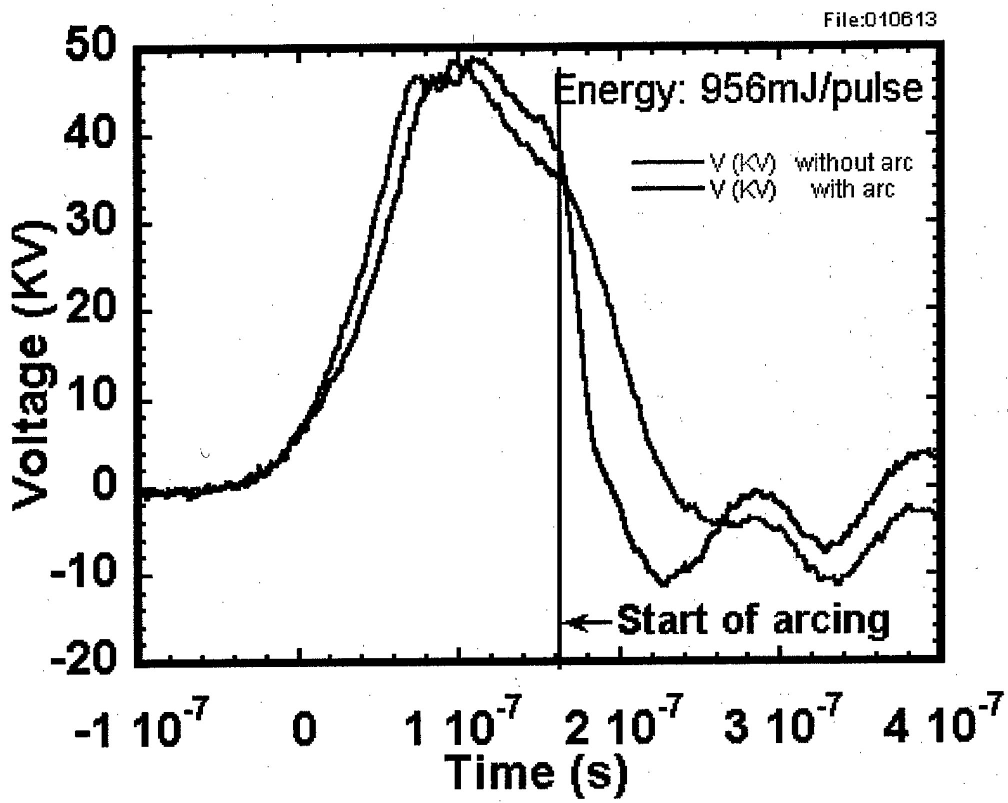

Figure 2: Transient plasma discharge waveforms: (b) voltage vs. time.

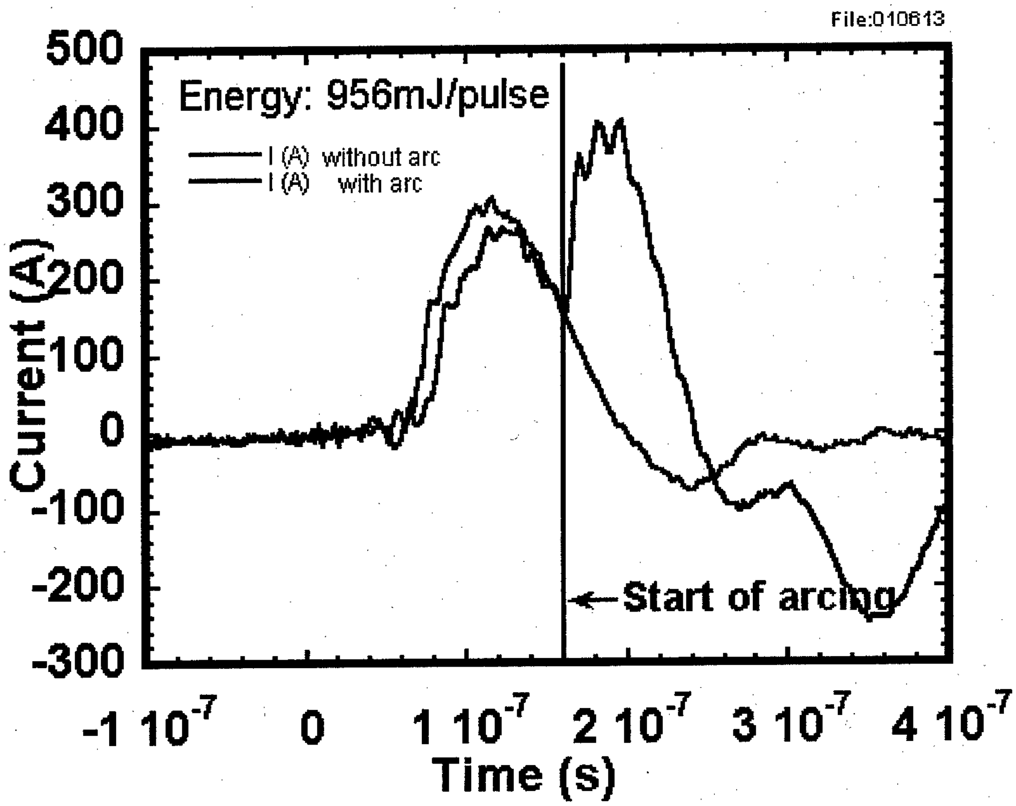

Figure 3: Transient plasma discharge waveforms: (c) current vs. time.

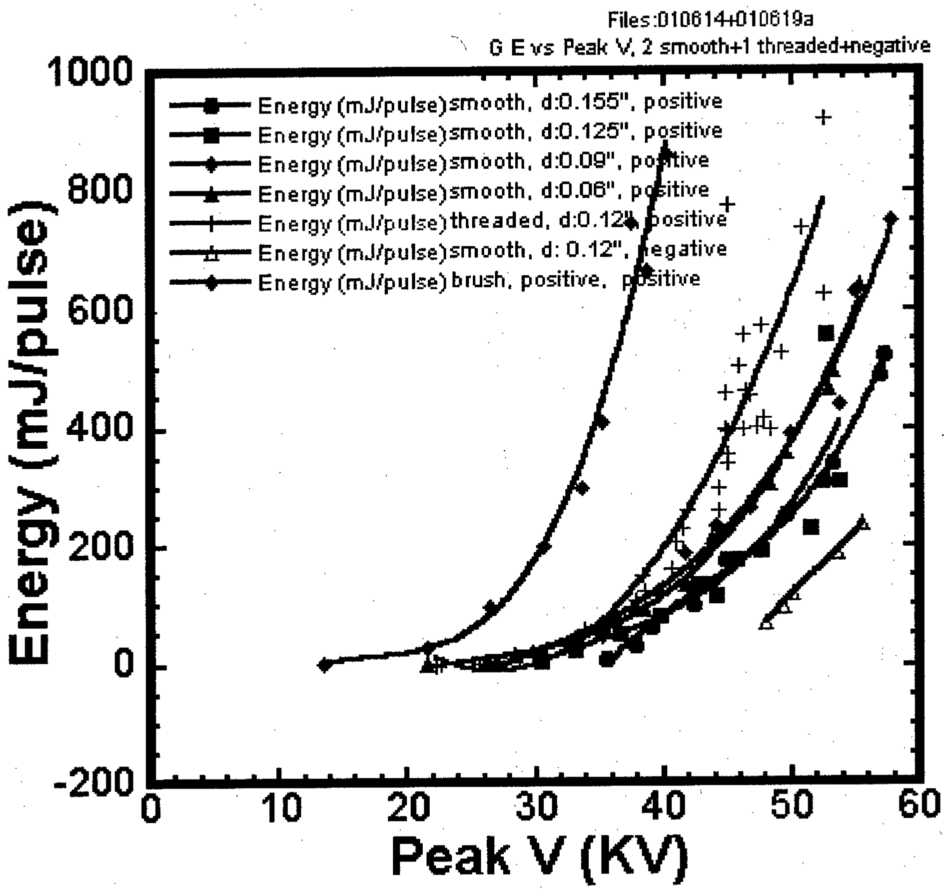

Figure 4: Electrode structure effect: energy vs. peak voltage for various electrode structures.

II. Combustion performance of various fuels:

Comparison between pulsed corona discharge and spark ignition

(1) CH_4/Air

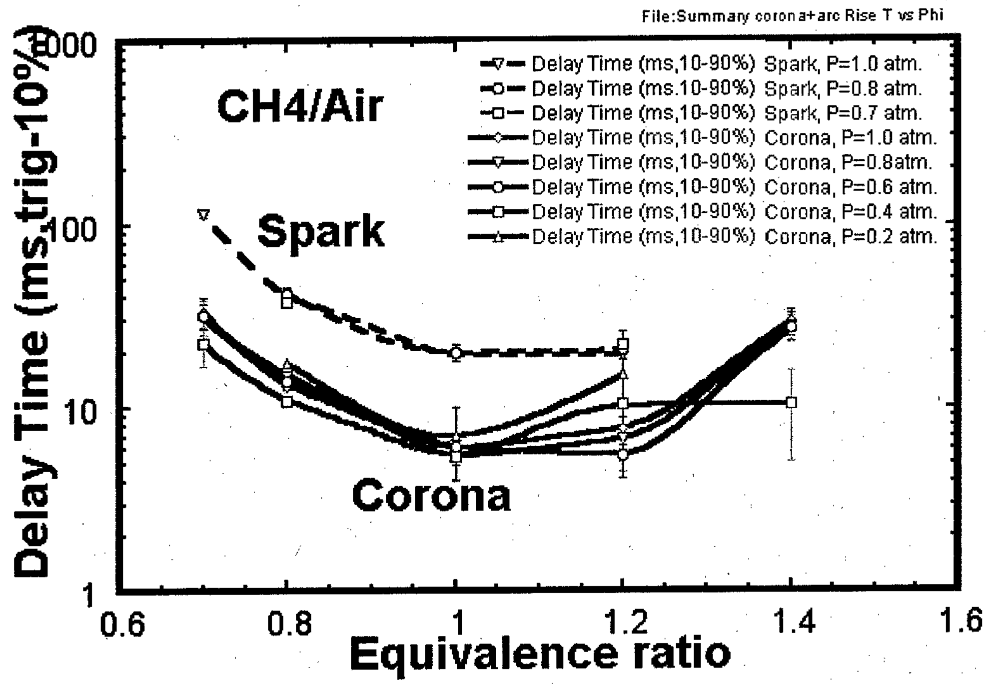

Figure 5: Combustion performance of transient plasma ignition and comparison with spark ignition : CH_4/Air, delay time vs. equivalence ratio for various pressures.

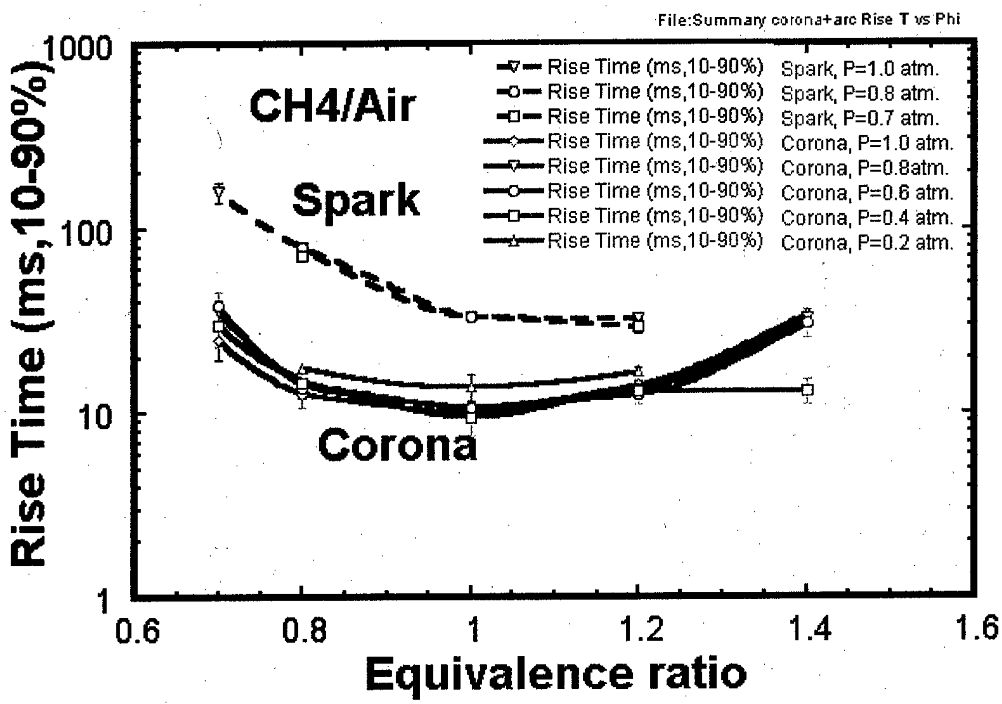

Figure 6: Combustion performance of transient plasma ignition and comparison with spark ignition : CH_4/Air, rise time vs. equivalence ratio for various pressures.

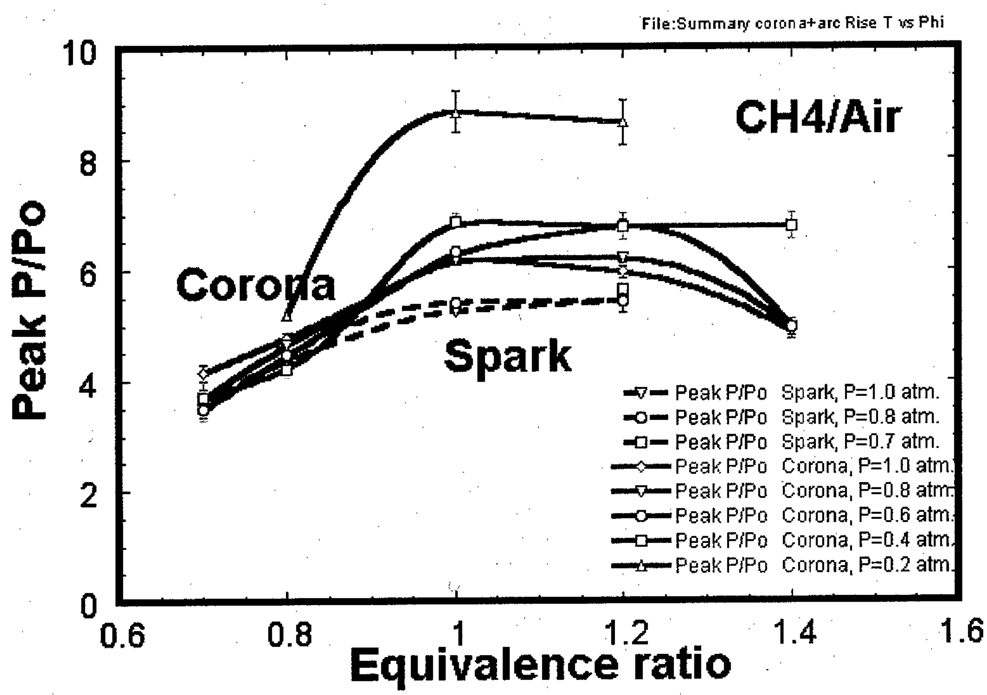

Figure 7: Combustion performance of transient plasma ignition and comparison with spark ignition : CH_4/Air, peak pressure vs. equivalence ratio for various pressures.

(2) C_3H_8/Air

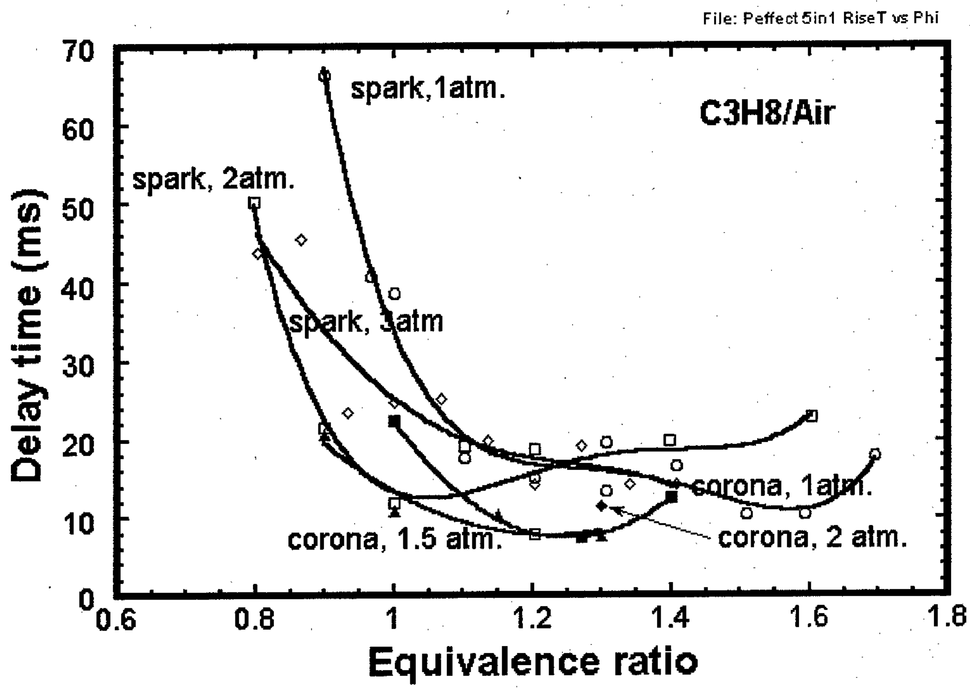

Figure 8: Combustion performance of transient plasma ignition and comparison with spark ignition : C_3H_8/Air, delay time vs. equivalence ratio for various pressures.

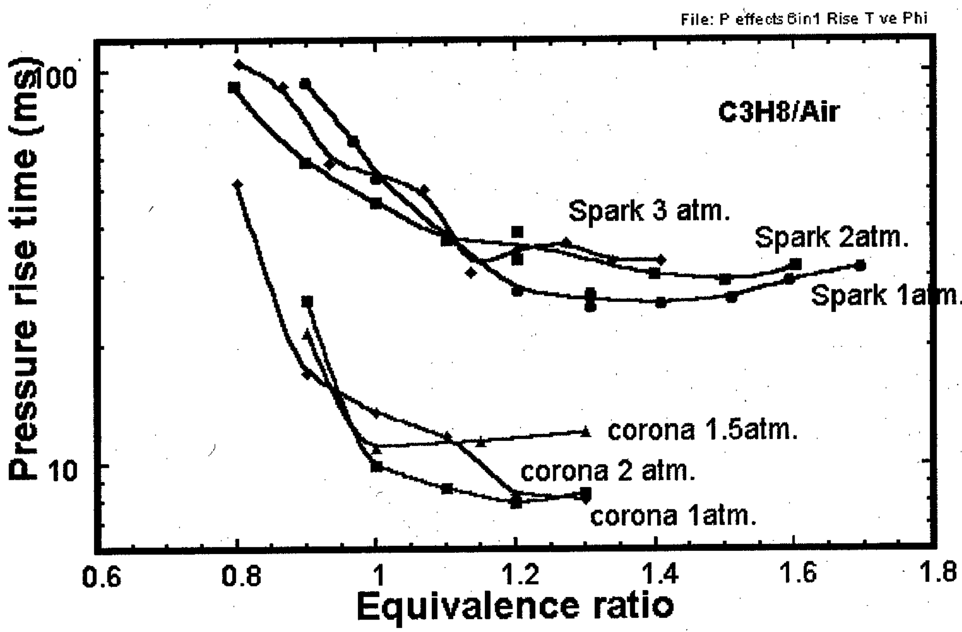

Figure 9: Combustion performance of transient plasma ignition and comparison with spark ignition : C_3H_8/Air, rise time vs. equivalence ratio for various pressures.

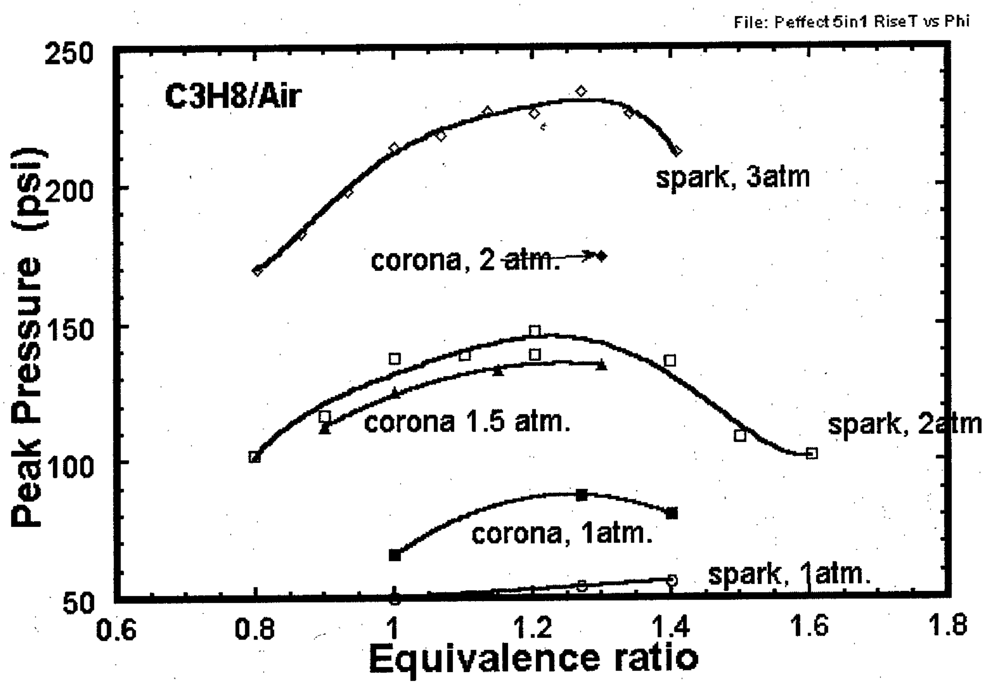

Figure 10: Combustion performance of transient plasma ignition and comparison with spark ignition : C_3H_8/Air, peak pressure vs. equivalence ratio for various pressures.

(3) C_4H_{10}/Air

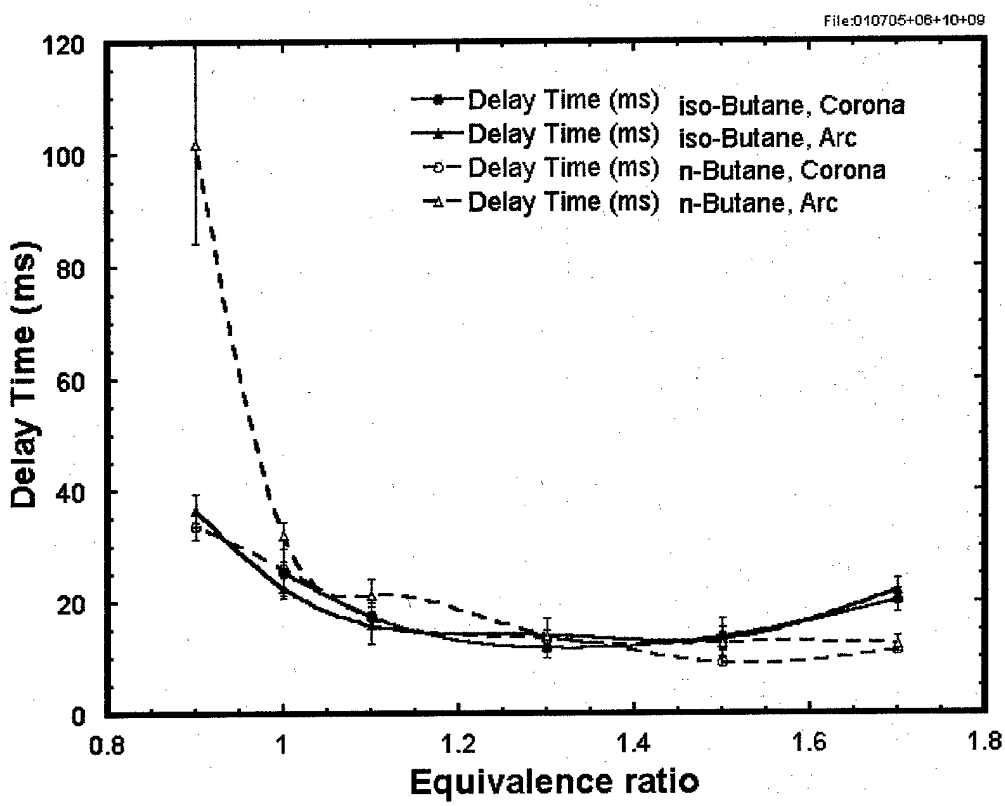

Figure 11 (a): Combustion performance of transient plasma ignition and comparison with spark ignition : C_4H_{10}/Air, delay time vs. equivalence ratio for various pressures.

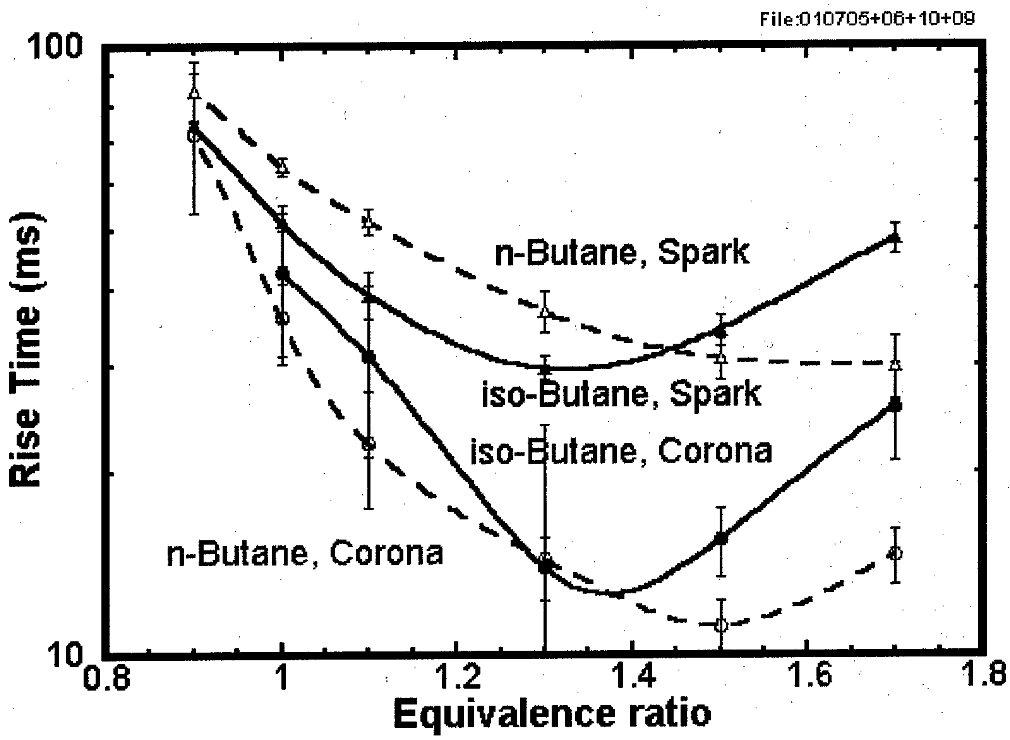

Figure 11 (b): Combustion performance of transient plasma ignition and comparison with spark ignition : C_4H_{10}/Air, rise time vs. equivalence ratio for various pressures.

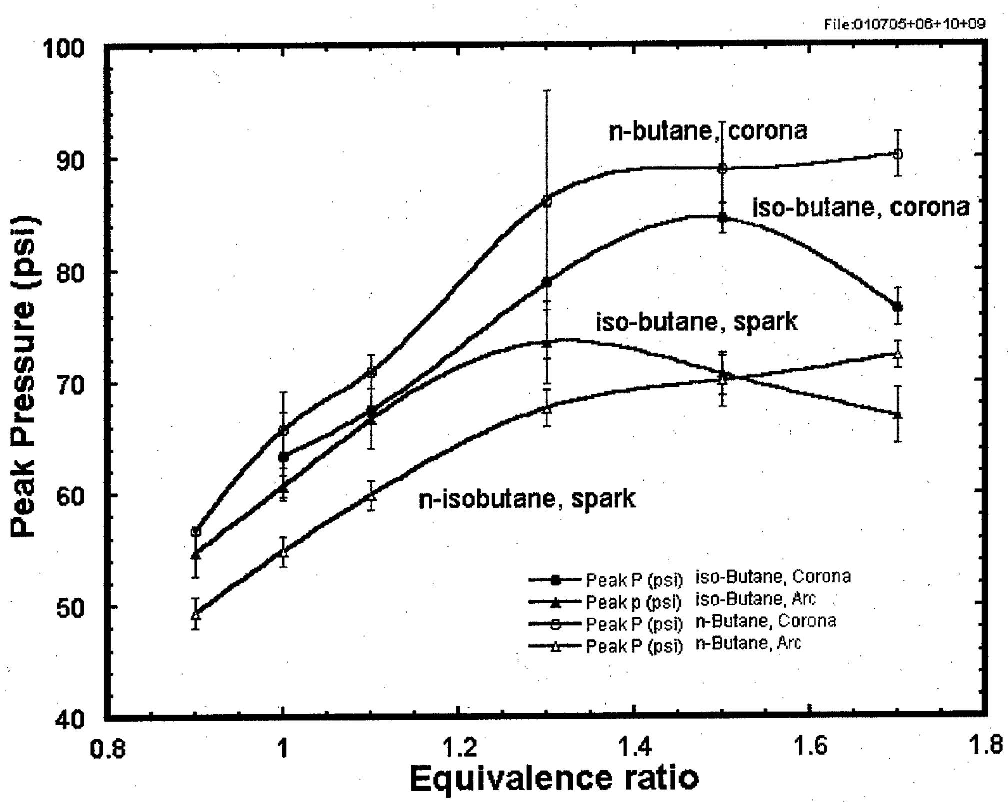

Figure 12: Combustion performance of transient plasma ignition and comparison with spark ignition: C_4H_{10}/Air, (c) peak pressure vs. equivalence ratio for various pressures.

(3) C_8H_{18}/Air

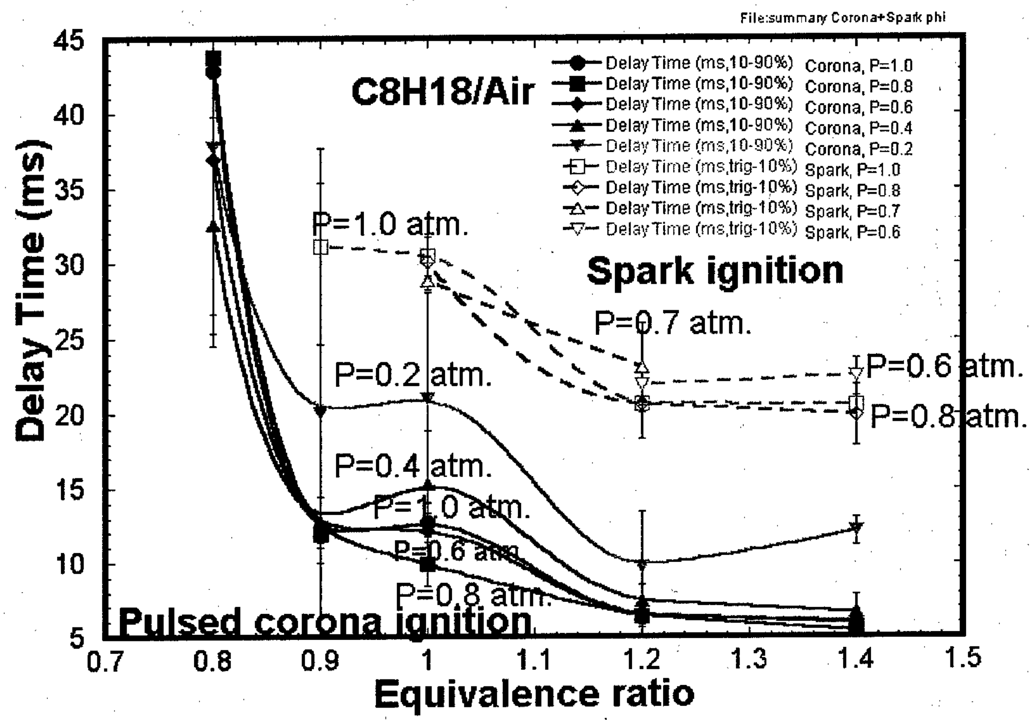

Figure 13: Combustion performance of transient plasma ignition and comparison with spark ignition : C_8H_{18}/Air, delay time vs. equivalence ratio for various pressures.

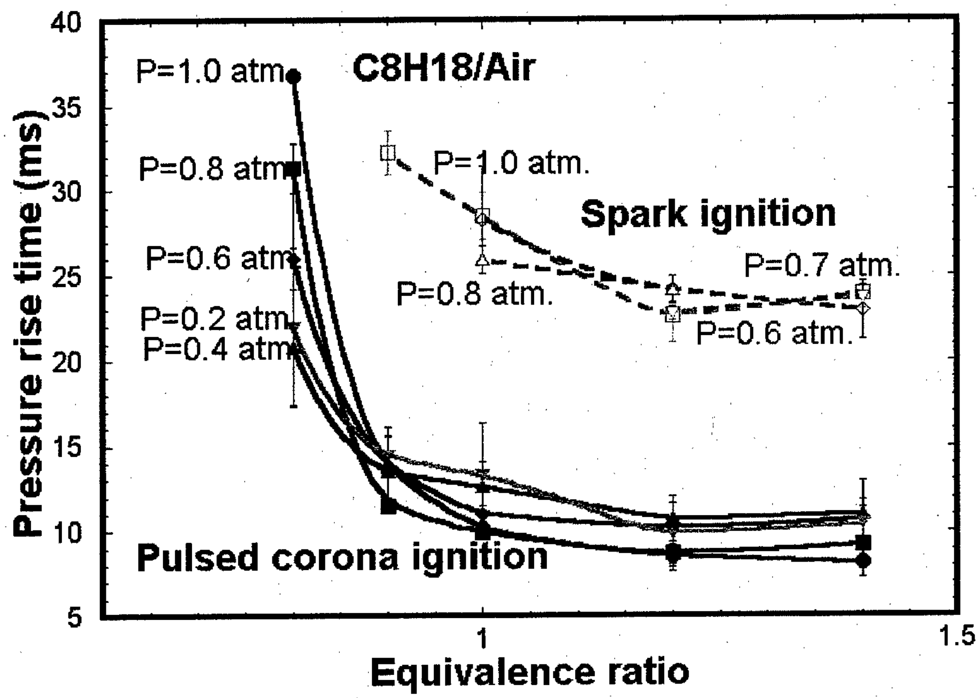

Figure 14: Combustion performance of transient plasma ignition and comparison with spark ignition: C_8H_{18}/Air, rise time vs. equivalence ratio for various pressures.

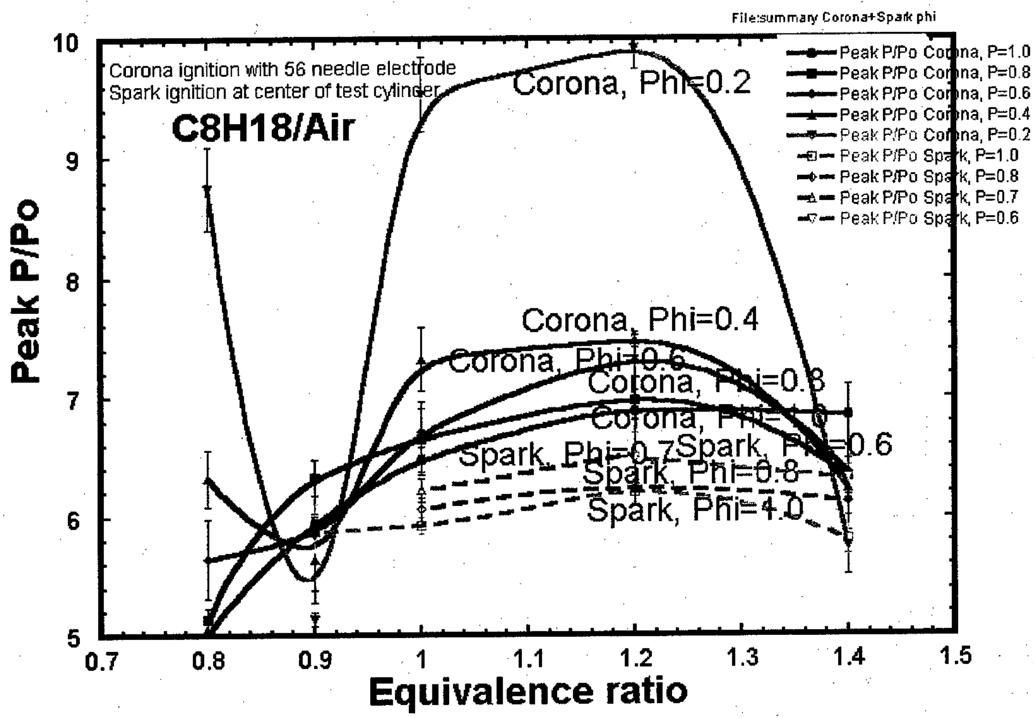

Figure 15: Combustion performance of transient plasma ignition and comparison with spark ignition : C_8H_{18}/Air, peak pressure vs. equivalence ratio for various pressures.

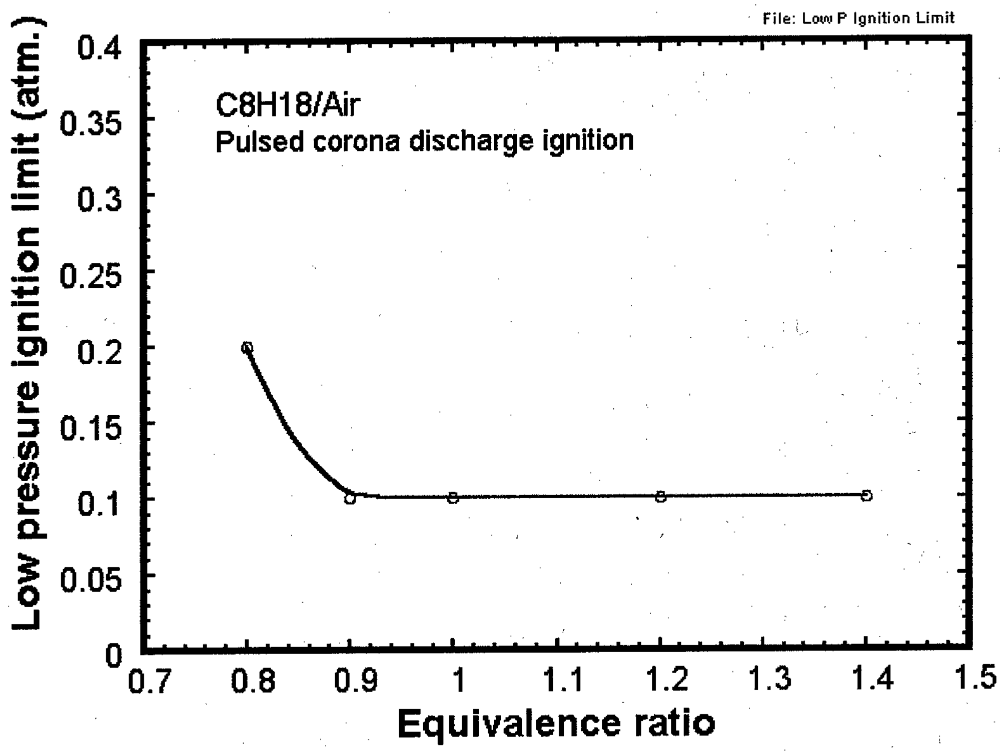

Figure 16: Low pressure ignition energy vs. equivalence ratio, C_8H1_8/Air.

III. Minimum ignition energy

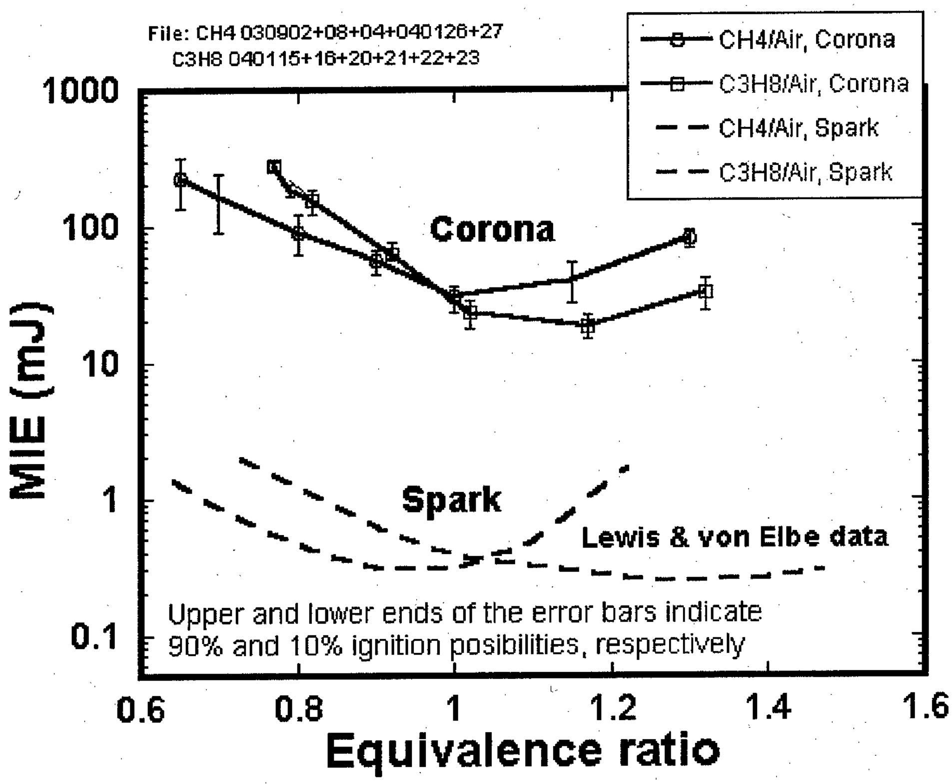

Figure 17: Minimum ignition energy of CH_4/Air and C_3H_8/Air vs. equivalence ratio by transient plasma discharge, and comparison with spark discharge ignition.

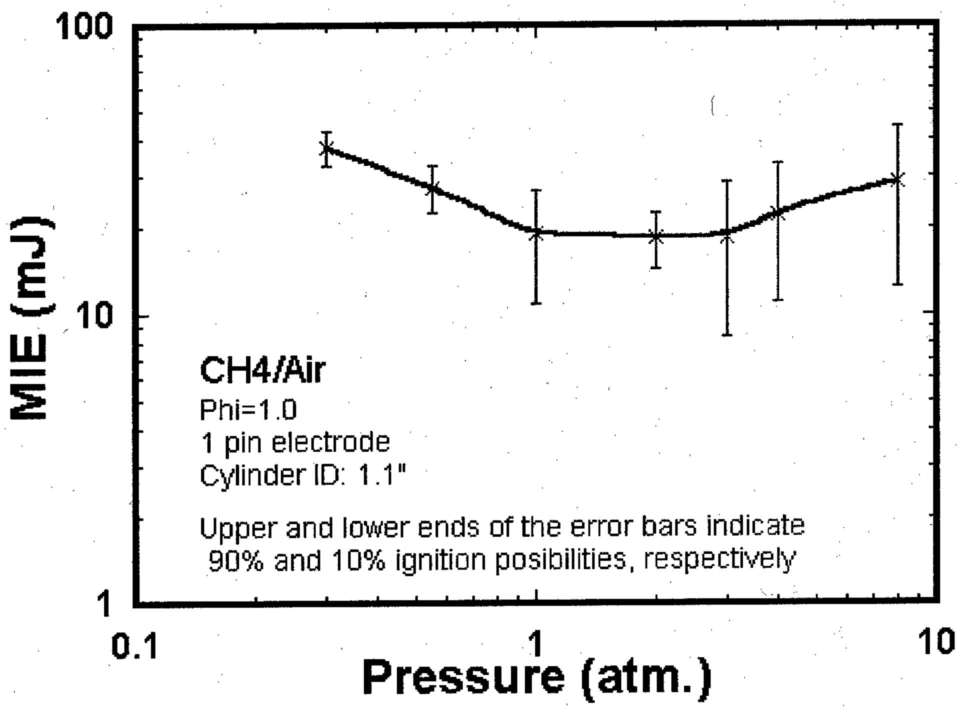

Figure 18: Minimum ignition energy of CH_4/Air vs. pressure. Electrode structure: 1 pin – cylinder.

IV. Pulsed corona ignition in a car cylinder like combustion chamber

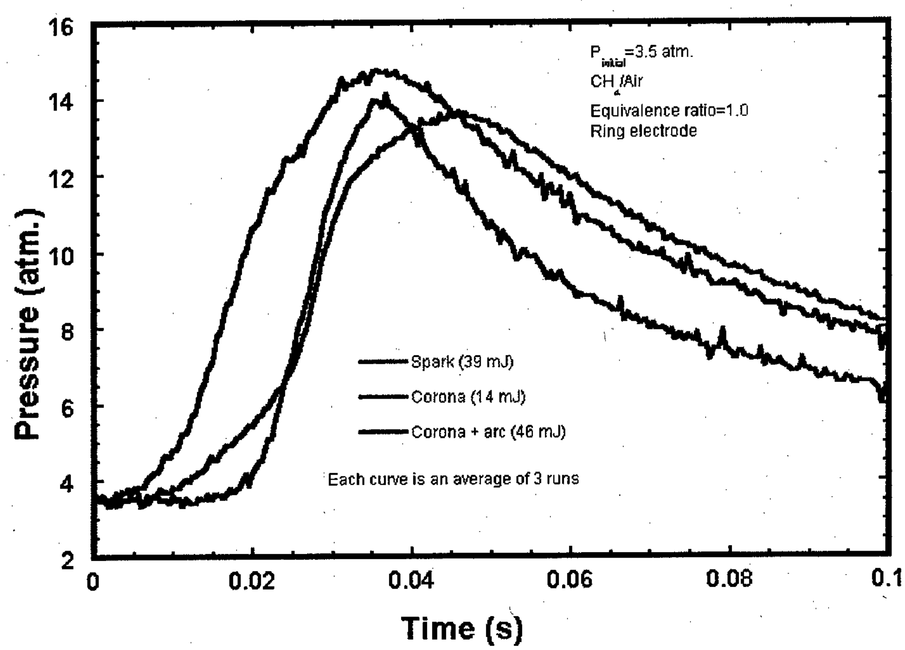

Figure 19: Pressure waveform in a car cylinder like combustion chamber and comparison with spark ignition. CH_4/Air.

V. Discharge efficiency

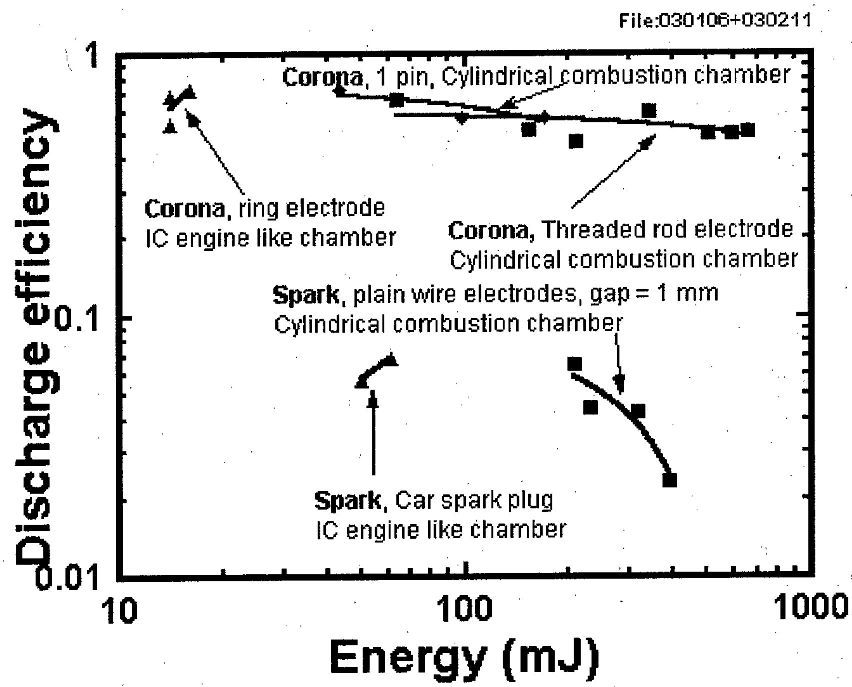

Figure 20: Discharge efficiency vs. discharge energy. Comparison between transient plasma and spark discharge in two different combustion chambers.

VI. Transient plasma ignition in turbulent flow

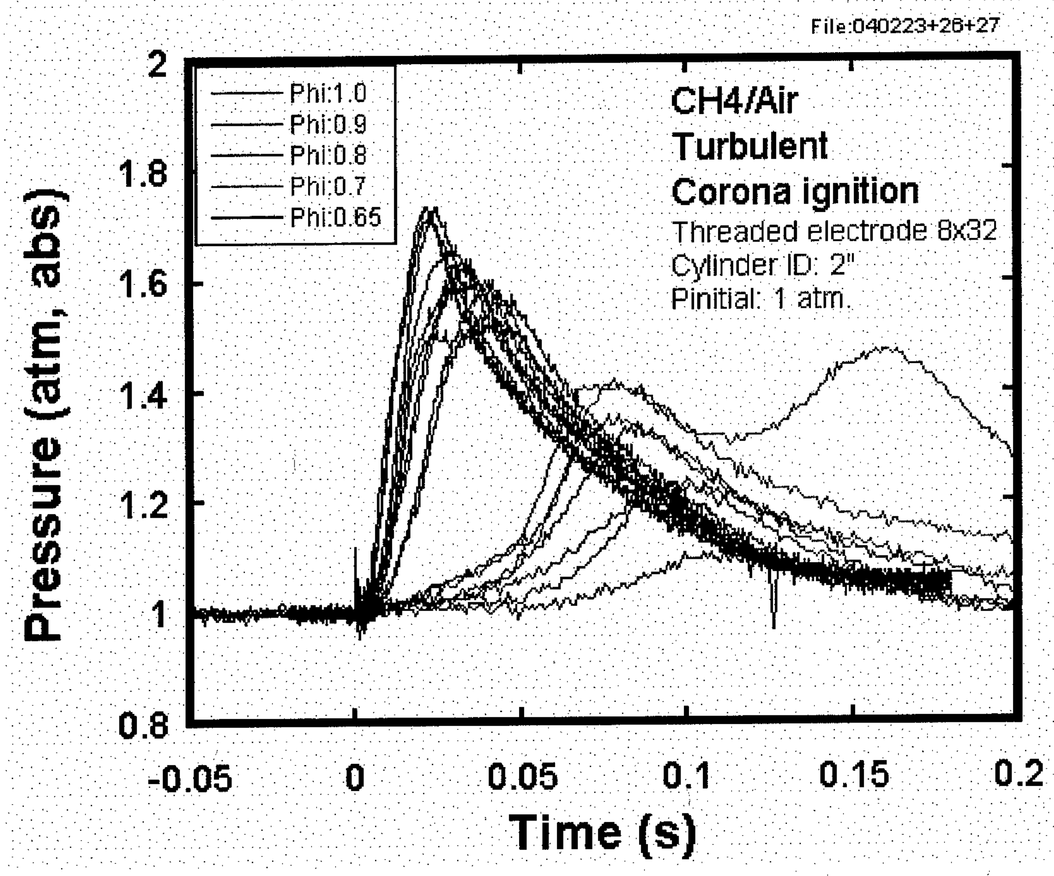

Figure 21: Pressure waveforms of transient plasma ignition in turbulent flow with various equivalence ratio. CH_4/Air. Electrode structure: threaded rod-cylinder.

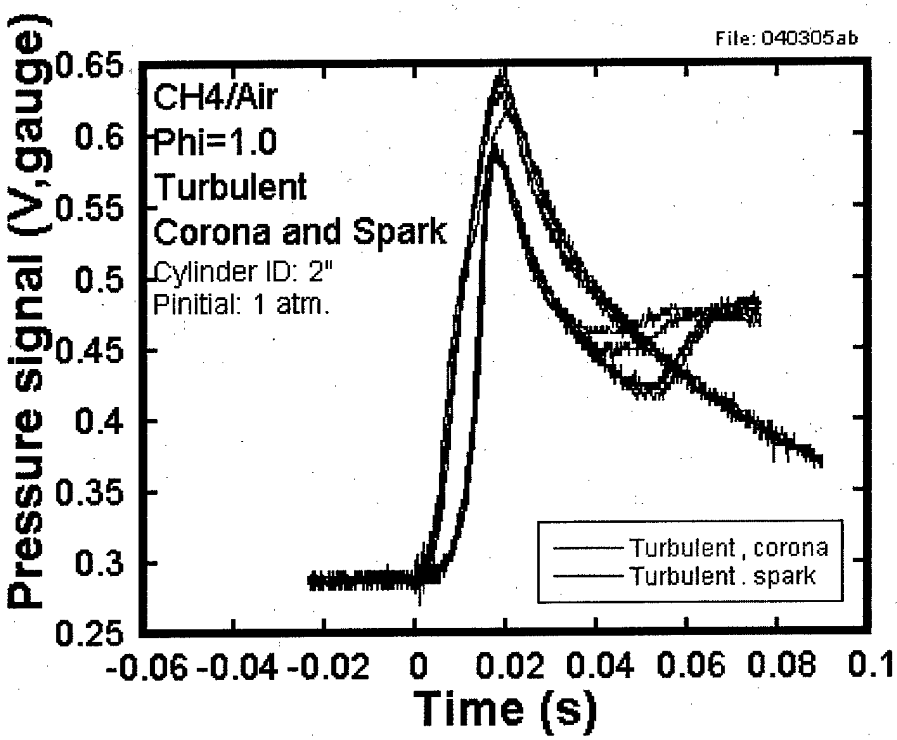

Figure 22: A comparison between pressure waveforms of transient plasma and spark ignition in turbulent flow.